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AIR-WATER GAS TRANSFER IN COASTAL WATERS

FINAL REPORT for ONR N00014-94-1-0050

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SUMMARY

The research was centered around a new experimental technique that uses heat as a proxy tracer to measure the air-sea gas exchange rate. The transfer rate for heat in water is measured by using a known heat flux density and measuring the temperature difference across the aqueous boundary layer. In contrast to geochemical methods that are based on mass balances and that have a slow response time in the order of days to weeks due to the larger vertical scales (typically the depth of the mixed layer), the controlled flux density gives an instantaneous 'picture' of the transfer process. Hence, direct insight into the transport processes right at the air-water interface is obtained through quantitative analysis of infrared image sequences of the water surface. Together with physical modeling of the underlying transfer processes, this *passive infrared radiometry* technique allowed the computation of the transfer rates directly from the statistical surface temperature distributions without artificial heating of the water surface.

The influence of wind forcing, short wind waves, and surfactants on the air-sea gas transfer in coastal waters was studied in field two experiments. The measurements include the air-sea gas transfer rates with a temporal resolution in order of minutes, the air friction velocity, water currents and turbulence, air and water temperatures, visible and infrared radiative fluxes, the visco-elastic properties of surface films, and wave number-frequency spectra of short wind waves. The measurements of the air-sea gas exchange rates with our instruments were combined with concentration measurements of carbon dioxide and dimethyl sulfide in the sea and the atmosphere, and direct flux measurements of carbon dioxide using the eddy correlation technique.

TASKS COMPLETED:

This new technique was used successfully to evaluate extended data sets acquired during two field experiments. The first field experiment took place during the MBL/COOP cruise in spring 1995 off the West Coast (Bock et al., 1995, Haussecker and Jähne, 1995). The cruise on the R/V New Horizon led from Monterey Bay along the California coast down to San Diego up to 30 sea miles off shore. Most of the measurements were performed around the Channel Islands. The second experiment took place in the Northwest Atlantic in June 1997 (Bock et al., 2000) between

the coastal waters of Martha's Vineyard Sound south of Cape Cod, MA, and the Bermuda Islands. It provided a rich data set including data obtained under a wide range of environmental conditions.

One drawback of *passive flux technique* lay in its need for an independent measurement of heat transfer. This drawback resulted from the fact that the model of surface renewal was underconstrained when using solely spatial statistics. The model required the use of a long time average for estimates of the heat flux. Current measurement techniques are combining different sensors and heuristic assumptions on water vapor transfer to calculate the individual fluxes that make up the net heat flux. Quite often the individual sensors are separated by a few meters which results in sparse spatial resolution and large systematic errors. Even with these strong limitations on spatial and temporal resolutions, measurements typically produce errors of about 30%. This turned out to be one major limitation in evaluating data from the 1997 field experiment. Therefore, the main focus was on the development of data analysis techniques that allow the direct estimation of the net heat flux across the water surface from the IR image sequences.

A novel motion estimation technique that incorporates the physical transport processes into the motion analysis (Haussecker et al., 1999) lead to an increased accuracy of the tracking of the heat patterns. This allowed for the extraction of the material derivative of the temperature with respect to time from a sequence of infrared images, compensating for the surface motion. From the material derivative, the probability density function of the underlying surface renewal model as well as the heat fluxes could be estimated. Measurements at the Aelotron wind/wave facility (University of Heidelberg, Germany) were conducted in spring of 2000 and results of the new technique agreed well with conventional measurements of the heat flux.

SCIENTIFIC RESULTS:

Both field campaigns yielded a large data set of gas transfer rates together with all relevant micrometeorological and turbulence measurements. The data reveal strong positive correlation between mean square slope, near surface turbulent dissipation, and wind stress. It also demonstrated a strong negative correlation between mean square slope and the fluorescence of surface-enriched colored dissolved organic matter. Additionally, observations made during rain events show a significant enhancement of the gas transfer velocity (Schimpf et al., 1999, Bock et al., 2000).

The data gave also direct insight into the mechanisms of air-sea gas transfer. In agreement with similar laboratory experiments, we could show that gas transfer process is governed by surface renewal with a lognormal renewal statistics (Jähne and Haussecker, 1998). The accuracy of the gas transfer data was not limited by the infrared images but by the accompanying heat flux measurements. It was required to measure the sensible, latent, and radiative heat flux density across the ocean surface in order to estimate the transfer velocity from the measured temperature differ-

ences. Unfortunately these measurements have a much large time constant than the IR measurements and proved to be of only limited accuracy. In principle, the *active thermography* technique avoids this problem by using an IR laser to heat a spot at the ocean surface. However, this technique was hampered by the fact that under most environmental conditions the heated spot drifted out of the measured footprint before it decayed sufficiently.

SIGNIFICANCE:

The new data from this project together with laboratory data obtained by the PI in previous investigations enabled a better physically based modeling of the air-sea gas transfer rate. Previous attempts (e.g., by Liss and Merlivat and Wanninkhof) model the gas transfer rate as a function of the wind speed alone. Our results show a strong correlation of the gas transfer rate with the mean square slope of the waves. While this correlation is better than with the wind speed or friction velocity alone, it does lack a clear physical understanding. However, by incorporating the influence of the mean-square-slope of the waves into a physically-based model, we were able to express two dimensionless quantities in the equation for the relation between friction velocity and the gas transfer velocity (the exponent of the Schmidt number dependency and the dimensional transfer resistance for momentum transfer across the aqueous viscous boundary layer) as a function of the also dimensionless mean-square-slope (Jähne and Bock, 2000).

Finally, we can say that the techniques developed during this project will be a major constituent in the upcoming NOAA GASEX-II cruise in the South Pacific during February 2001.

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AWARDS:

German Association for Pattern Recognition (DAGM '99) conference award for the two contributions:

"A total least squares framework for low-level analysis of dynamic scenes and processes", authored by H. Haussecker, C. Garbe, H. Spies, and B. Jähne.

"Differential range flow estimation", authored by H. Spies, H. Haussecker, B. Jähne, and J. L. Barron.